UNCLASSIFIED

AD 268 094

Reproduced
by the

ARMED SERVICES TECHNICAL INFORMATION AGENCY
ARLINGTON HALL STATION
ARLINGTON 12, VIRGINIA

UNCLASSIFIED

829 800

WADD TECHNICAL REPORT 61-185

FEASIBILITY STUDY OF VIBRATION AND SHOCK EXCITER USING ELECTRIC FIELD MODULATION OF HYDRAULIC POWER

JOHN J. EIGE
EDWARD C. FRASER

STANFORD RESEARCH INSTITUTE
MENLO PARK, CALIFORNIA

JULY 1961

62-1-4

XEROX

WRIGHT AIR DEVELOPMENT DIVISION

FEASIBILITY STUDY OF VIBRATION AND SHOCK EXCITER USING ELECTRIC FIELD MODULATION OF HYDRAULIC POWER

JOHN J. EIGE
EDWARD C. FRASER

STANFORD RESEARCH INSTITUTE
MENLO PARK, CALIFORNIA

JULY 1961

ENGINEERING TEST DIVISION
FLIGHT AND ENGINEERING TEST GROUP

WRIGHT AIR DEVELOPMENT DIVISION
AIR RESEARCH AND DEVELOPMENT COMMAND
UNITED STATES AIR FORCE
WRIGHT-PATTERSON AIR FORCE BASE, OHIO

FOREWORD

This report has been prepared by Stanford Research Institute under USAF Contract AF 33(616)6942 entitled, "Vibration Shock System." This work is covered under Project 1309, "Flight Vehicle Environmental Investigations," Task 13002, "Environmental Simulation Methodology."

The program was monitored by the Environmental Branch, Engineering Test Division, Wright Air Development Division, under the direction of Robert W. Sevy, Project Engineer.

References are made in this report to material contained in Interim Scientific Report Number 1, "Vibration Shock System" covering the period 2 January to 31 August 1960. A limited number of report copies are available upon request by referring to the government project engineer, attention following symbol: WWFEVD.

This report covers the period of work from December 1959 to March 1960.

ABSTRACT

This report covers the conclusion of a feasibility study of the use of magnetic fields controlling shear stresses in magnetizable fluids and of electric fields controlling shear stresses in electrically active fluids, for driving a high-power, high-frequency vibration and shock exciter.

To avoid repetition, references are made to the Interim Scientific Report 1 for this project, covering the initial studies and preliminary designs for a prototype. This final report is concerned with the actual design, construction, and testing of a prototype shock-shaker, as well as further investigations of electric fluids. A theoretical analysis of the electric-fluid mechanics is presented.

The prototype demonstrated the technical feasibility of electric-field valving of hydraulic power in a shock-shaker. The peak accelerations and frequency bandwidth were less than the specifications because of deliberate lack of refinement of this first experimental model and because the only available fluid had a lower sensitivity than the earlier fluids which were previously evaluated and upon which the design was based. However, it appears that further research could lead to a useful shock-shaker and many other applications.

PUBLICATION REVIEW

The publication of this report does not constitute approval by the Air Force of the findings or conclusions contained herein. It is published only for the exchange and stimulation of ideas.

FOR THE COMMANDER:
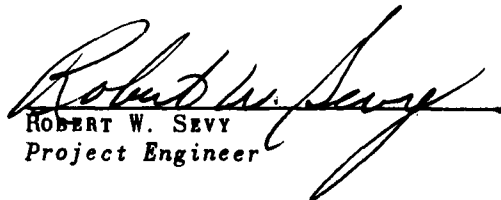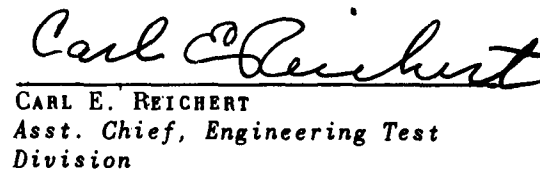
JOSEPH DAVIS, JR.
Colonel, USAF
Commander
Flight and Engineering Test Group

Concurred in:

Robert W. Sevy
Project Engineer

Concurred in:

Carl E. Reichert
Asst. Chief, Engineering Test
Division

Concurred in:

Hugh S. Lippman
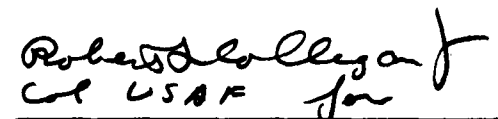Technical Director

Approved by:

Joseph Davis, Jr.
Colonel, USAF
Commander
Flight and Engineering Test Group

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

VIBRATION-SHOCK SYSTEM

I INTRODUCTION

A. STATEMENT OF THE PROBLEM

The objectives of this project were to investigate the principles of
a proposed shock and vibration exciter and to make a prototype of such a
device as appeared feasible. Primary consideration was to be given to the
use of hydraulic power, modulated by the effect of a magnetic or electric
field on a suitable type of hydraulic fluid. The goal was a high-
acceleration, wide-frequency-band exciter, capable of both sinusoidal wave
shape (vibration) and square waves of acceleration (shock).

Interim Scientific Report 1, September 1960, covered the first phase
of this project. That phase consisted of a basic study of some magnetically-
responsive and some electrically-responsive fluids in order to determine the
most promising approach to the prototype design.

This final report covers actual design, construction, and testing of
the prototype shock-shaker, as well as further investigations of properties
of electric fluids.

B. BACKGROUND

The experiments and references cited in the Interim Report show that
it is possible to make modulating valves with no moving parts by applying
either a magnetic or an electric field to the appropriate fluid. In the
electric case, the valve is basically two parallel plates, insulated from
each other and separated by a small gap through which the fluid can flow.
As voltage is applied across the two plates, the resistance to flow in-
creases. At a given field strength (volts per unit of gap thickness)
a minimum pressure differential must be supplied to cause any flow at all,
giving the effect of a closed valve below that pressure. This response
of a fluid to an electric field is called the Winslow Effect.

Use of an electrically— (rather than magnetically—) responsive fluid was recommended in the previous report because it appeared to allow simpler construction, fewer problems with wear and fluid separation, and less likelihood of high-frequency limitations. Preliminary designs were given for both a valve-controlled and a clutch-type drive for a prototype.

We met with the Project Engineer from WADD in October 1960, and agreed to use an electric fluid and valve-type control for the prototype.

C. METHODS AND SCOPE

In Phase I of this project, we evolved an empirical description of the important variables in an "electrohydraulic modulator" (EHM). We then made various assumptions about how four of them could be improved and made to work together in a shock-shaker system in order to meet particular specifications. Testing the resulting prototype allowed a check on the design theory, and more data from which to revise and improve the theory, as well as practical experience with operating conditions which could not be accurately predicted.

The following sections contain a description of the prototype and its performance, as well as some further studies of electric fluids. A promising refinement of the mathematical description of the electric-fluid mechanics is given, with recommendations for methods using it as the basis of an improved design theory.

II DESIGN OF THE PROTOTYPE SHOCK-SHAKER

A. GENERAL

The general design of the prototype follows that given in Appendix A of the Interim Report. As shown in Figs. 1 and 2 of the present report, four EHMs (valves) control flow to and from the output ram in push-pull fashion. The accumulators and flexible hose upstream of modulators M_1 and M_4 are intended to smooth out pump pulsations and give approximately a constant-pressure source. Small petcocks with drain lines are used to bleed air out of high points in the system. The ball valve in the main return line can be partially closed while running the pump to create a high pressure throughout the system to force trapped air out of the petcocks. Air bubbles would decrease the system's stiffness and therefore slow its response, and could cause arcing inside the modulators.

A modified commercial hydraulic cylinder was used as the output ram. It is double-acting, double-ended, and flange-mounted, with a 1½-inch bore and 1-inch stroke. The effective area of the cylinder cross section was calculated to be 1.46 in². In order to reduce friction, the piston rings and all but one chevron-type rod seal at each end were removed, and the built-in dash-pot-type cushioned ends of the piston were machined off.

The modulators are mounted to the ram with short, stiff connections (steel pipe nipples) in order to allow high-frequency response. The modulators are functionally similar to the experimental one described in the Interim Report—essentially a cylindrical capacitor with fluid allowed to flow axially in the annular gap between the inner slug and the outer shell. Figure 3 shows a cross section of an EHM, partly dimensioned, with a detail sketch of the voltage connection. The fittings allow a high voltage to be led into the inner slug, and the electrical lead to be easily detached, without leakage of the pressurized fluid. The nylon parts proved to have the required strength, flexibility, machinability, and dielectric strength. The outer parts are made from Nylo-Seal tubing fittings (The Imperial Brass Mfg. Co.), which happen to hold well on RG-59/U coaxial cable.
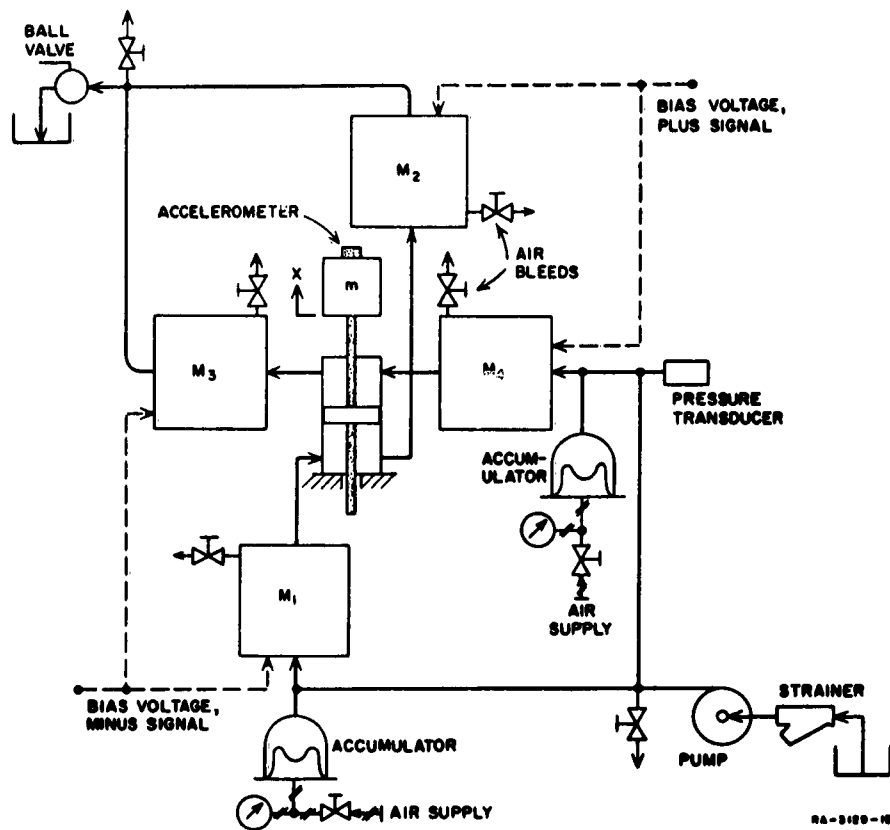
FIG. 1

FLOW DIAGRAM OF PROTOTYPE SHOCK-SHAKER

FIG. 2(a)

TOP VIEW OF PROTOTYPE SHOCK-SHAKER

FIG. 2(b)
SIDE VIEW OF PROTOTYPE SHOCK-SHAKER

6

NYLON PARTS

RG-59/U

INNER INSULATION

WASHER SOLDERED TO INNER CONDUCTOR, BUTTED AGAINST WIRE

WIRE PRESSED INTO NYLON

WASHER SOLDERED TO WIRE

O-RING, 4.000" OD X 0.139" WIDE, BOTH ENDS

BORE ID:	4.000"
PLUG OD:	3.997
GROOVE OD:	3.778
GROOVE WIDTH:	0.187

$\frac{1}{8}$" NPT (FOR BLEED)

0.040" ±0.002

$\frac{1}{8}$" R

(HOLLOW SPACE)

3"

PRESS FIT

PHENOLIC PLUGS, 8 PLACES, $\frac{1}{4}$" D, PRESSED IN

PHENOLIC PLUGS, 8 PLACES, $\frac{3}{8}$" D, PRESSED IN

$\frac{1}{2}$" NPT BOTH ENDS

$\frac{1}{4}$" R

6-32 X $\frac{1}{2}$", 16 HOLES

FIG. 3

CROSS SECTION OF A MODULATOR USED IN THE PROTOTYPE

B-3129-18

7

The inner slug was made hollow to reduce its mass and the insulating spacers were stiff in an attempt to avoid low-frequency resonances which might interfere with smooth over-all frequency response. The end plates of the inner slug and of the outer shell are made thick to avoid "drumhead" resonances for the same reason. Aluminum's low density, high stiffness, good conductivity, corrosion resistance, machinability, and economy made it well suited for the metal parts of the EHMs. Phenolic was chosen for the insulating spacers for its good stiffness, dielectric strength, mechanical strength, absence of brittleness, and availability in rod form.

The base plate of one inch steel plate not only serves as a rigid base for the components of the shock-shaker, but it greatly adds to the mass which the output cylinder reacts against. A large reaction mass and/or rigid fastening to the ground are required so that the shock-shaker does not bounce at high accelerations, limiting and distorting the acceleration of the load. Bolt holes are provided in the base plate for fastening it to a concrete foundation.

The 2.5-pound cube of brass screwed onto the top end of the piston rod simulates a useful load mass. The mass of the accelerometer on top of the cube, plus the mass of the piston, totals 1.4 pounds.

B. ELECTRICAL EQUIPMENT

The electrical circuits used to excite the EHMs are shown in Fig. 4. Since the electrical work is ancillary to the main effort of this project, no attempt was made to design or construct the ideal driving circuits. Rather, in the interest of economy, the equipment was constructed for the most part of presently owned components. It is presumed that improved performance could be realized if the excitation equipment were specifically designed for this application.

The exciter consists basically of a source of DC bias voltage, to which is added the desired signal, which is an AC voltage for sinusoidal vibration. Since two of the modulators must be driven 180° out of phase with the other two, the addition of the DC and AC voltages is accomplished by means of a transformer with two isolated, high-voltage, secondary windings. These windings are connected in phase opposition between the DC supply and their respective pairs of modulators. The primary winding of the transformer is supplied from the output transformer of a 60-watt linear audio amplifier and oscillator. The 150-K resistor shown connected across

8

each secondary, is to provide proper loading for the amplifier output
stage. The potentiometer connected between the two transformer second-
aries and the DC supply, permits unbalancing the bias voltage applied to
the two pairs of modulators, and thus allows manual control of load
position. It was found that the range of resistance required for this
application was so high as to introduce considerable losses into the
circuit. It is anticipated that in any future designs, this method of
balancing would be replaced with an adjustable DC voltage source which
could be inserted in either branch of the circuit as desired.
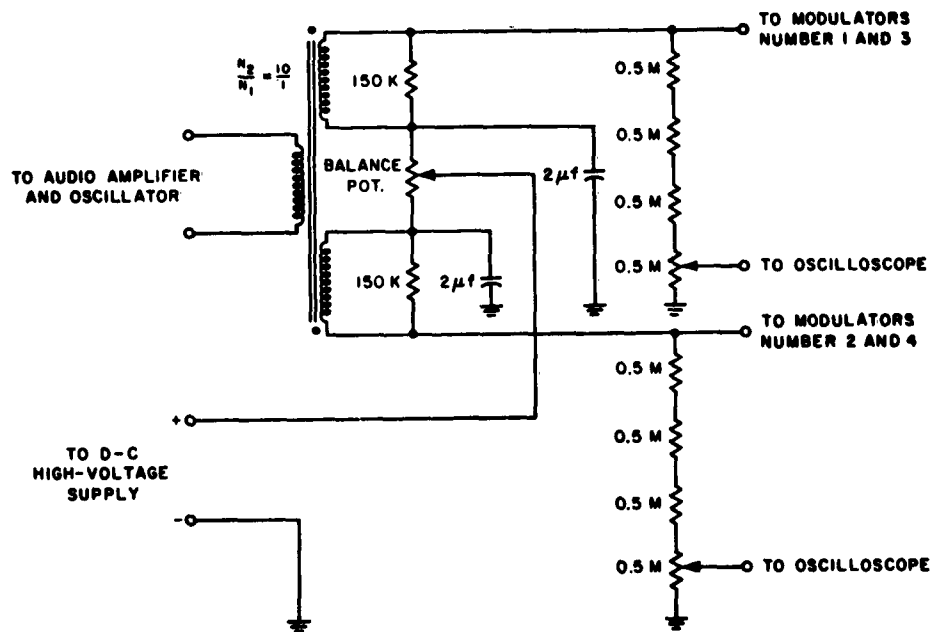
FIG. 4

ELECTRICAL EXCITATION CIRCUIT

The two capacitors on either side of the balancing potentiometer
serve to provide a low impedance path to ground for the AC components of
the signal, bypassing the relatively high internal impedance of the DC
source. The resistors connected in parallel with each pair of modulators
provide adjustable low-voltage taps to allow monitoring of the excitation
waveshape with an oscilloscope or other measuring equipment.

9

As it is presently operating, the system is completely open-loop. No use has been made of either position or acceleration feedback. Provision has been made for acceleration feedback through a crystal accelerometer and suitable amplifiers and compensating networks. However, the time schedule of the project, and the low system gain encountered, did not allow the incorporation of feedback into the system. Similarly, it is anticipated that position feedback could be used to maintain the load automatically in the center of the power piston stroke. No effort has been expended in this direction, however. Should future work be done in this area, it is recommended that the electrical excitation equipment be designed and constructed in close coordination with the requirements of the EHMs involved.

III. TESTS OF THE PROTOTYPE SHOCK-SHAKER

The hydraulic fluid used was purchased from Warner Electric Brake and Clutch Company. Their label identifies the liquid as "Electrofluid 127 RE, Batch PO 60-41." It was quite viscous and thixotropic as provided, so we thinned it with the recommended redistilled kerosene until it had approximately the viscosity of ordinary hydraulic oil. The thinning was necessary to reduce viscous pressure drop through the modulators and viscous friction on the ram, and to allow entrained air bubbles to rise quickly in the liquid in the sump, and thus escape.

Equipment was set up to provide compensated acceleration feedback to the electrical control circuit in order to flatten the frequency-response curve and to reduce distortion, but the only tests we have made to date have been without feedback (*i.e.*, open-loop).

A list of the test equipment used, with a brief description of each item is given in the Appendix of this report.

A. DYNAMIC CHARACTERISTICS

Frequency response of the prototype was measured by applying the maximum DC bias voltage which our supply could maintain, and superimposing the desired AC signal voltage in push-pull fashion. The bias voltage applied to modulators M_1 and M_3 was adjusted to be enough greater than that to M_2 and M_4 so that the weight of the piston and load was supported, and the piston was kept centered by manually adjusting the balance potentiometer. The average bias voltage was 1500 VDC in all runs described here. Thus, the signal voltage could be as much as 3000 volts peak-to-peak before overmodulating. However, the voltage which our AC supply would provide to the prototype fell off with increasing frequency.

The criterion given in Appendix A of the Interim Report assumes that the peak total voltage should be equal to the bias voltage times the square root of two. The criterion was intended to allow the use of a constant supply pressure (into M_1 and M_4), since the pressure drop at peak voltage is assumed equal to the drop at zero signal voltage. The above calls for a peak-to-peak alternating voltage of 0.828 times the bias level, or, in this case, 1240 VAC.

11

Figure 5 shows the ratio of acceleration output to sinusoidal signal voltage, both measured peak-to-peak. At any one frequency, the above amplitude ratio does not change appreciably with varying signal voltage, at least up to 1240 VAC peak-to-peak, indicating that response is linear with respect to signal voltage over that range. The low point at 200 cps shows the maximum output of 29 times the acceleration of gravity ("g units") for a 3-kv signal, where the ratio had dropped due to an undetermined saturation effect.
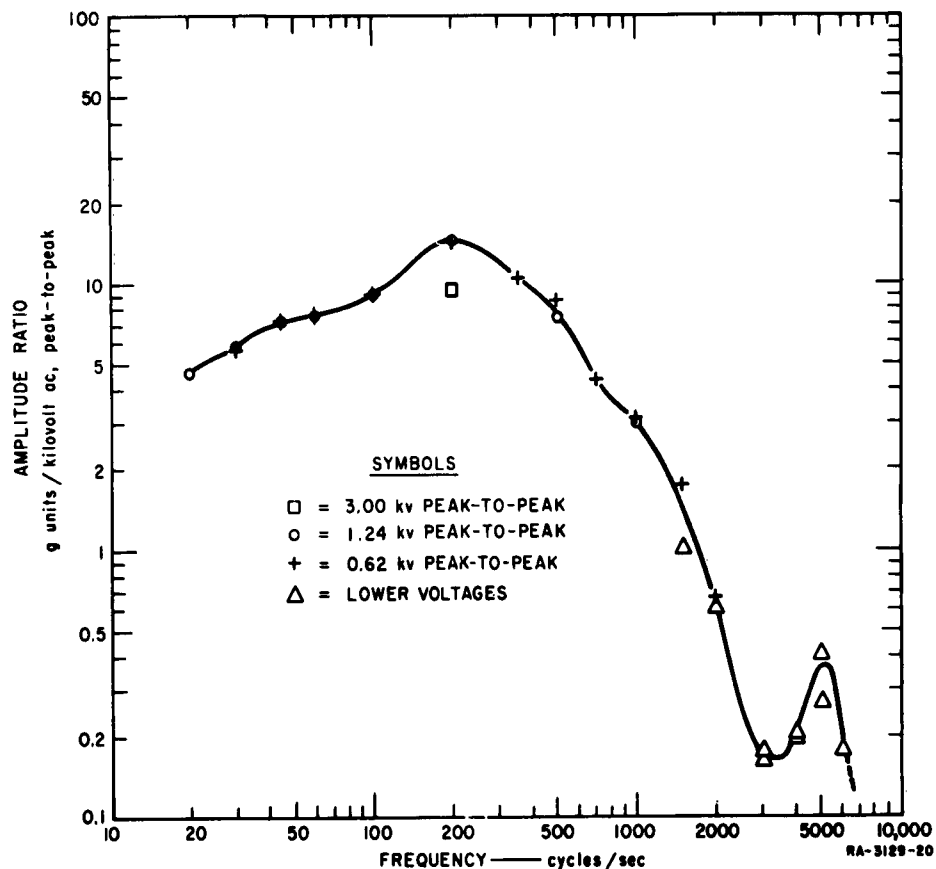
FIG. 5

OPEN-LOOP FREQUENCY RESPONSE OF SHOCK-SHAKER WITH 1500-VDC BIAS

12

Typical waveforms of acceleration and control voltage, as seen on an oscilloscope, are shown in Fig. 6. In each picture, acceleration is the upper trace, and the lower trace represents voltage to one pair of modulators, measured from zero at the bottom horizontal line. The oscilloscope beams were swept from left to right at a steady rate for each picture. The notch in each peak of the 20 cps response could have been caused by the prototype not being bolted down during the tests and bouncing slightly.

(a)
20 cycles/sec
2.72 g units/cm
500 volts/cm
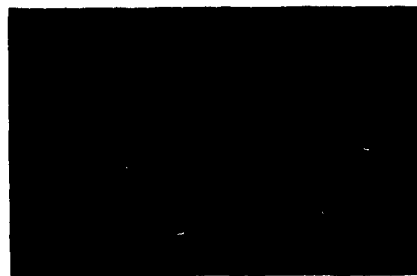
(b)
200 cycles/sec
6.80 g units/cm
500 volts/cm
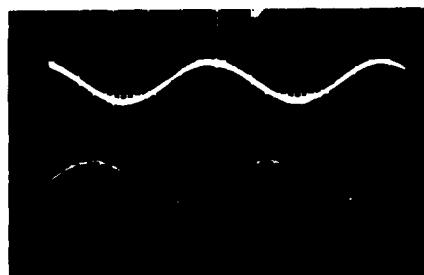
(c)
2000 cycles/sec
0.68 g units/cm
500 volts/cm

(d)
500 cycles/sec, square wave
2.72 g units/cm
500 volts/cm

RA-3129-21

FIG. 6

TYPICAL WAVEFORMS OF SIGNAL VOLTAGE (LOWER TRACE)
AND RESULTING ACCELERATION (UPPER TRACE)
AT VARIOUS FREQUENCIES

13

The 500-cps square-wave test, indicated in Fig. 6(d), shows several limitations. The amplitude which could be applied without serious high-frequency attenuation was limited by the transformer used to step up the control voltage. The acceleration waveshape could probably be made more square by use of the proper feedback and, more basically, by very careful redesign to avoid even minor resonances anywhere near 500 cps.

B. POWER REQUIREMENTS

The prototype was designed for a maximum hydraulic-power dissipation of 360 watts average at 60 cps and 30 g units. To meet that specification, the pump must deliver about 10 gpm at 100 psig.

The electrical losses in the modulators were found to be significant in the present design. Data relating direct current drawn by the four modulators in parallel to applied steady voltage could be fitted, to a first approximation, by the equation:

$$I = 2(10)^{-12}V^3 \text{ amperes} \tag{1}$$

where V is in volts. Accordingly, the instantaneous dissipation in any pair of electrically paralleled modulators would be:

$$P = \frac{VI}{2} = \left(\frac{V}{10^3}\right)^4 \text{ watts peak.} \tag{2}$$

It appears that the peak dissipation increases rapidly with peak voltage, being roughly 1 watt for 1 kilovolt, but 81 watts at 3 kilovolts. The capacitance of the modulators was not measured.

14

IV STUDIES OF FLUIDS RESPONSIVE TO ELECTRIC FIELDS

A. MATHEMATICAL ANALYSIS OF ELECTRIC-FLUID MECHANICS

We related in the Interim Report that pressure drop through an EHM
seemed to have the form:

$$\Delta P \;=\; RQ \;+\; C_0 \,\frac{L}{\epsilon}\, S \tag{3}$$

where

$$R \;=\; \text{laminar flow resistance, } 12 \; \mu L/w\epsilon^3$$

$$Q \;=\; \text{volume flow rate}$$

$$C_0 \;=\; \text{a constant (assumed to be unity)}$$

$$L/\epsilon \;=\; \text{length-to-gap ratio, and}$$

$$S \;=\; \text{fluid shear stress due to applied electric field} \\ \text{(assumed constant at all points in the gap).}$$

We had also established that, within the range of our trials, the shear
stress due to field was proportional to the square of the applied field,
as follows

$$S \;=\; \alpha E^2 \tag{4}$$

where the value of the proportionality constant, α, depended upon the
particular fluid (composition, dilution, contamination, etc.) used. From
torque measurements in the cylindrical clutch of our previously described
electroviscometer, we determined the value of α for various fluids and
predicted the pressure drop of the EHMs.

Recent experiments with the identical fluid in the electroviscometer
and the EHMs of the prototype indicated that if α as measured in the elec-
troviscometer were correct, then C_0 in Eq. (3) should be between 2 and 3,
instead of the assumed value of 1. The following analysis gives a rational
basis for believing that such is the case. Any consistent set of units may
be used for finding numerical values.

15

An EHM will be represented in a mathematical model by a pair of parallel flat plates, L long by w wide, and ϵ apart, with voltage V across them (see Fig. 7). Thus, the electric field strength, $E = V/\epsilon$.
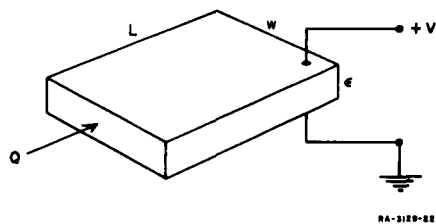
FIG. 7

THEORETICAL MODEL OF AN EHM

Assume fully developed laminar flow. Therefore, the pressure is constant throughout any cross section perpendicular to the flow direction, and the velocity profile is the same at all sections.

Since there is no net momentum flux through the ends of the control volume, the momentum equation for a control volume centered inside the passage (see Fig. 8) reduces to a balance of forces:

$$\Sigma F_x = 0.$$

$$\Delta P \cdot 2yw - 2\tau Lw = 0 \tag{5}$$

where τ is the shear stress in the fluid (as a function of y).
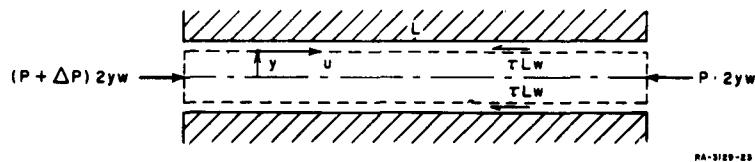
FIG. 8

CROSS SECTION OF MODEL EHM, SHOWING CONTROL VOLUME

Evaluate Eq. (5) at $y = \epsilon/2$:

$$\Delta P \cdot \epsilon w - 2\tau_m Lw = 0 \tag{6}$$

where τ_m is the value of shear stress at the boundary.

16

Divide Eq. (5) by Eq. (6) to find the shear stress distribution:

$$\tau = \frac{y}{\epsilon/2} \tau_\blacksquare$$ (7)

The above says that shear stress increases linearly from zero at the center line to a maximum, $\tau_\blacksquare$, at each wall. This distribution is shown in Fig. 9.
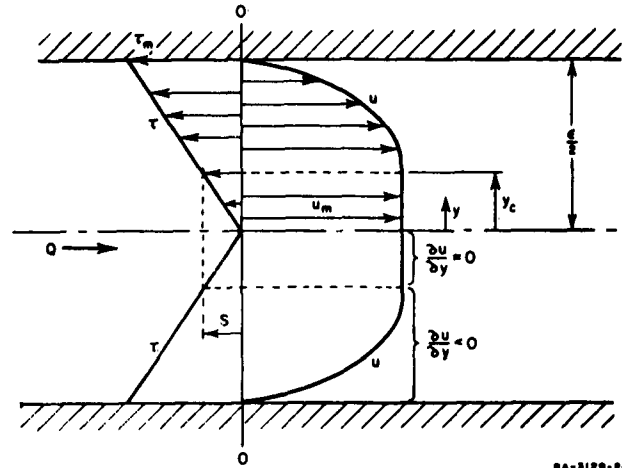
FIG. 9

SHEAR STRESS AND VELOCITY PROFILES IN MODEL EHM

To find the velocity profile, assume that the shear stress at any point in the fluid is the sum of the ordinary viscosity effect and the electric field effect, S—that is:

$$\tau = -\mu \frac{\partial u}{\partial y} + S$$

or,

$$\frac{\partial u}{\partial y} = -\frac{\tau - S}{\mu}$$ (8)

Further assume that there can be no relative motion between adjacent lamina of fluid as far as the shear stress (which increases linearly out from the center line) can be supported by the electric field effect.

17

After τ exceeds S, slip occurs between all lamina further out toward the walls. The velocity gradient, $\partial u/\partial y$, must then be zero in some center portion of the passage, and negative in the outer portions where τ is greater than S.

Substitute τ from Eq. (7) into Eq. (8), and integrate to find the velocity profile in the outer region, as follows:

$$- \mu \int_{y}^{\epsilon/2} \frac{\partial u}{\partial y}\, dy \;=\; \int_{y}^{\epsilon/2} \left(\frac{\tau_{\blacksquare}}{\epsilon/2}\, y \;-\; S \right) dy$$

$$\mu u \;=\; \frac{\tau_{\blacksquare}}{\epsilon/2} \left[\frac{(\epsilon/2)^2}{2} - \frac{y^2}{2} \right] - S \left(\frac{\epsilon}{2} - y \right) \quad .$$

Let:

$$Y \;\equiv\; \frac{y}{\epsilon/2} \quad .$$

Then:

$$\mu u \;=\; \frac{\tau_{\blacksquare}\,\epsilon}{4} \, (1 - Y^2) \;-\; \frac{S\epsilon}{2}\, (1 - Y) \tag{9}$$

The maximum velocity, $u_{\blacksquare}$, occurs at the critical distance, y_c, where $\tau = S$ and $\partial u/\partial y = 0$. If we define

$$Y_c \;\equiv\; \frac{y_c}{\epsilon/2} \quad , \tag{10}$$

then $u_{\blacksquare}$ is expressed by substituting Y_c for Y in Eq. (9). The velocity profile is seen to be flat in the center region of the gap and parabolic in the outer regions, as shown in Fig. 9.

Now the velocity can be integrated across the passage to find the flow rate, Q, as follows:

18

$$Q \;=\; 2w \int_0^{\epsilon/2} u\,dy$$

$$=\; 2wu_a y_c \;+\; 2w \int_{y_c}^{\epsilon/2} u\,dy$$

$$=\; wu_a Y_c \epsilon \;+\; w\epsilon \int_{Y_c}^{1} u\,dy \qquad . \tag{11}$$

Y_c can be evaluated by solving Eq. (7) at $y = \dot{y}_c$ and $\tau = S$, giving

$$Y_c \;=\; \frac{S}{\tau_a} \qquad . \tag{12}$$

An alternative expression can be found by solving Eq. (6) for τ_a, giving

$$\tau_a \;=\; \frac{\epsilon/2}{L}\,\Delta P \tag{13}$$

and by combining Eq. (13) with Eq. (12), as follows:

$$Y_c \;=\; \frac{2LS}{\epsilon\Delta P} \qquad . \tag{14}$$

Eq. (11) can now be evaluated:

$$Q \;=\; \frac{1}{R}\left[\Delta P \;-\; \left(3 - Y_c^2\right)\frac{L}{\epsilon}S\right] \qquad . \tag{15}$$

Solving for ΔP gives

$$\Delta P \;=\; RQ \;+\; \left(3 - Y_c^2\right)\frac{L}{\epsilon}S \qquad . \tag{16}$$

It is interesting to compare equation 16 with the previously assumed form of the pressure drop, Eq. (3). The term in parentheses varies from 2 to 3, depending upon flow conditions, as was indicated by the previously mentioned experimental data. Even for the limiting case where field effects are strong compared to viscous effects, and Y_c approaches unity, the value of C_0 should have been 2 instead of 1, as mistakenly used before. That erroneous assumption did not affect the prototype design values because the same equation that was used to define α from tests of an EHM, was used to predict the performance of the later models.

A similar analysis for a clutch-type device, such as the electroviscometer, indicates a constant shear stress at all points in the gap (as was assumed previously) and a linearly increasing velocity profile. Thus, the analysis confirms the equations upon which measurements of α in the electroviscometer were made.

B. PROPERTIES OF WARNER ELECTROFLUID

The Warner Electrofluid, described in Sec. III, was obtained especially for tests of the prototype shock-shaker and was somewhat different from the type of Warner fluid tested previously. The present fluid is more stable physically. That is, we no longer had problems with drying out in open containers, drying into a solid inside the pump or piping, or with excessive precipitation of the suspended solids. The thinned fluid separated somewhat over a period of days, but it was easily stirred up again. Abrasion of the rubbing surfaces in the pump was found after testing was completed, but it caused no problems during the tests. No voltage breakdown was observed up to our working field strength of at least 3 kilovolts per millimeter. The current-vs.-voltage measurements mentioned in Sec. III indicate that the resistivity of the fluid drops rapidly with increasing voltage.

The Electrofluid was tan-colored in its original condition. When voltage was applied across it, and it was tested in either the electroviscometer or the prototype, it quickly turned a dark gray. It was not determined whether this darkening was accompanied by a decrease in α, because the process of trying to test new fluid changed it to darkened fluid before the tests were completed. A likely cause of the darkening could be carbon particles formed by the decomposition of a part of the fluid under the action of shear and electric current.

Chemical analysis of the Electrofluid here at the Institute indicated that it is similar to the formulation originally described by Winslow in

20

the references given in the Interim Report. Solid particles are suspended in an oily liquid. The particles are quite small, at least 99 percent of them being less than one micron in diameter. The major component of the solids appeared to be silica gel, and the liquids were hydrocarbons and possibly polysiloxanes. Only traces of metallic ions, other than silicon, were found.

The value of α for the new unthinned fluid was measured in our electroviscometer at 0.2 psi/(kv/mm)^2. After thinning and use in the prototype, the fluid had an α of 0.05 psi/(kv/mm)^2, as measured in both the electroviscometer and the EHMs of the prototype.

C. OTHER ELECTRIC-FIELD-RESPONSIVE FLUIDS

At a time when it appeared that fluid for testing the prototype might not be available commercially, we made some brief tests of other possible fluids by means of the electroviscometer.

We postulated that particles of high dielectric constant immersed in a liquid of much lower dielectric constant should tend to form chains (or some other, more complex structure) across a gap in the presence of an electric field, and thus resist a shearing action. The liquid should be a good insulator to avoid arcing and to reduce the electrical current required. In our tests, a low-viscosity silicone oil (DC 200, 10 centistoke) was the oil referred to below.

Other staff members who were consulted suggested that for the particles of high dielectric constant we might try barium titanate or metallic powders. A perfectly conducting metal would have an infinite dielectric constant, but must be covered by an insulating layer (such as its oxide or the oil) to avoid a short-circuit across the gap. We also tried powdered silica gel in some mixtures, as suggested by Winslow's work.

In general, either barium titanate or silica gel by itself in the oil gave an α of up to 0.016 psi/(kv/mm)^2, with no voltage breakdown up to at least 3 kv/mm. Addition of some iron oxide powder to either mixture increased α up to as much as 0.047 but brought the breakdown strength down to below 1 kv/mm. Aluminum powder had similar effects, but was less advantageous.

All mixtures which exhibited the Winslow Effect followed the square-law response reported above. This was readily observed by exciting the

21

electroviscometer with an alternating voltage (with no DC bias) and seeing that the torque output followed a sine wave of double the input frequency. Note that the square of a sine wave is a constant plus a sine wave of twice the original frequency.

When some of the powdered silica gel was dried over a hot plate before mixing it with the oil, no response could be measured. When the remaining dried powder was then slightly moistened with distilled water before com-- bining it with more oil, the response returned. Perhaps silica gel's affinity for water results in minute droplets of water with fairly high dielectric constant being held separated by an insulating matrix of silica gel.

A quantitative correlation of α to properties of the fluid constit- uents was not attempted.

V CONCLUSIONS

Tests of the prototype show that a vibration exciter is feasible using EHMs. Use of the design theory detailed in the Interim Report led to good linearity and sinusoidal waveshape even without feedback. The use of acceleration feedback should give flatter frequency response, and together with refinement of mechanical design to maximize stiffness and avoid resonances, should allow good enough square wave response so that the shaker could also be used as a shock-testing machine or random-vibration generator.

It would be desirable to find a fluid which gives a stronger effect so that the size of the EHMs could be decreased and less electrical current required. A higher resistivity of the fluid would also decrease the amount of current required.

This first prototype did not meet the desired sinusoidal acceleration specification, given in the proposal request, of 30 g peak vector for a 2.5-pound mass load over the frequency range of 60 to 2000 cps. The experimental open-loop response peaked at 29 g peak-to-peak at 200 cps, but fell off as shown in Fig. 5. The fact that the Electrofluid turned out to be ten times less effective than we had designed for, seriously reduced the response. We partially compensated for that reduction by raising the control voltages and drawing much more current, but did not have enough gain to afford acceleration feedback, which would have flattened the response curve by cutting off the peak. The peak voltage could not be maintained at all frequencies. With higher-rated electrical power supplies and circuitry the voltages to the prototype could be raised somewhat more. A peak voltage of 6 kv, with appropriate bias, should give quadruple the response we got at 3 kv, but it might draw 1.3-kw-peak electrical power. The present wiring is not designed for such a load, and a maximum voltage of 3 kv is recommended.

The proportions of the prototype seemed to be quite reasonable, except that the ram diameter might be increased to raise the output force, if the high-frequency response does not suffer from increasing the piston mass and the size of the flow passages. The materials and hardware used

23

proved satisfactory. Some abrasion of the pump was found, but measurements of its seriousness were not made. The system did not heat up perceptibly while running. The fluid was kept in an open reservoir for weeks without appearing to evaporate or oxidize.

A new theoretical analysis of electric fluid mechanics indicates that our original equation for pressure drop in an EHM was inaccurate, but it did not affect the validity of the preliminary design calculations.

The proposal request for this contract calls for an outline of a design of a shock-shaker to drive a 500-pound mass load. Such a device could be scaled up from the preliminary design procedure given in the Interim Report, but it is felt that it would be premature at this time before carrying out the research recommended in the following section.

The present first prototype is designed to be readily constructed, tested, and modified. It has not been developed and refined yet into a production machine.

VI RECOMMENDATIONS

The EHM-controlled shock-shaker appears promising enough to warrant further effort, now that its technical feasibility has been demonstrated.

Succeeding work would be on a firmer basis if we could gain a quantitative understanding of the Winslow Effect. The cooperation of the staffs of Warner Electric and Pure Oil Companies should be sought for their considerable experience in this field. A basic study should be aimed toward such goals as (1) being able to predict the strength of the effect from known properties of a fluid, (2) finding whether resistivity can be increased without weakening the Winslow Effect, (3) predicting an optimum fluid and estimating how far present ones are from it. Long-term stability of the fluids should also be considered. The economic future of electric-fluid devices could be estimated more accurately after having the above information.

More research could profitably be performed using the present proto-type shock-shaker. Measurements of pressure drop *vs.* steady flow rate and bias voltage would give additional checks on the validity of the fluid mechanics relationships derived in this report. Installation of pressure transducers at the bleed taps of the EHMs and flow transducers in series with each EHM would allow investigation of the validity of the original design assumptions specifying the fraction of the cycle during which each EHM would be flowing.

If the fluid mechanics analysis herein is upheld (or modified) by the above experiments, then a new look should be taken at ways to control a shaker with the better-understood EHMs. Use of an analog computer (available at the Institute) may be indicated at this stage in order to solve the simultaneous, nonlinear dynamic equations. Areas of potential research include (1) the question of whether a constant-pressure or constant-flow hydraulic source would be more efficient, (2) design of the electrical excitation to fit its load requirements, (3) computation of the best feedback compensation to reduce distortion and flatten response, and (4) a design study aimed at optimizing the proportions of the system.

A new model could then be built, incorporating the indicated improvements. A final model could be made more compact, for instance, by wrapping the EHMs around the output ram in concentric cylinders having integral flow connections at the ends. The piston would be designed for minimum mass and friction, or possibly replaced by a flexible diaphragm.

The program outlined above would provide the basis for design of many devices besides shock-shakers, such as position servomechanisms, clutches, and other fast-acting devices.

APPENDIX

EQUIPMENT LIST

1. Pump, Eco Model PP-2M, bronze with neoprene impellers, 10.7 gpm, 100 psig.

2. Accumulators, Special Products Co., 3A-15, 2000 psig max, 15-cubic inch.

3. Power supply, G. A. Philbrick Researches, Inc., Model R-100B, ±300v, for feedback computing amplifiers.

4. Pressure Transducer, Standard Controls Model SP2P-750G-350TC, 750 psig.

5. Accelerometer, Endevco Model 2215.

6. Hydraulic cylinder, Ortman-Miller THBB DA, 1½-in bore × 1-in stroke, double-ended.

7. Audio signal generator, Hewlett-Packard, Model 205AG.

8. Low-frequency function generator, Hewlett-Packard, Model 202A.

9. Audio power amplifier, McIntosh, 60-watt.

10. Voltohmmeters, Triplett, Model 630-NA.

11. Oscilloscopes, Tektronix, Types 502 and 551, with Types Q and CA plug-in units.

12. Autotransformer, General Radio "Variac," Type No. 1702-A, for motor control.

13. Motor, Master Electric, DC, 3/4 hp.

14. High-voltage DC supply, Furst Electronics, Model 810-O.

15. Force transducer, Kistler Model 601, piezoelectric.

16. Electrometer amplifier, Kistler Model 655.

17. Drill press, Magna Engineering Corp., "Shopsmith Mark V."

18. Pressure gages, Marshalltown Manufacturing Co., 0-200 psig.